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Synchronous droughts and floods in the Southern Chinese Loess Plateau since 1646 CE in phase with decadal solar activities

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Abstract

Droughts and floods are two longstanding and devastating climatic threats to mankind. They are challenging to predict mainly due to the significant spatial and temporal variations of precipitation. Using historical archives back from 1646 CE, here we present a high-resolution catchment level dataset of droughts and floods in the southern Chinese Loess Plateau (hereafter, CLP) within the middle reaches of River Jing. We have analysed the occurrences of floods and droughts based a specially-developed statistics from historical archives, as well as the daily rainfall from present-day observations within the catchment. Overall, our results show that the frequency of droughts and floods in the region is synchronous on decadal timescales with solar activities and the Pacific Decadal Oscillation (hereafter, PDO) index, and they are also broadly in phase with changes in both global and regional reconstructed temperatures. At decadal to interannual timescales, PDO and El Niño and Southern Oscillation (hereafter, ENSO) drive an uneven distribution of precipitation in different seasons in the southern CLP, which could be one of the reasons for the strong association of floods and droughts with the PDO and ENSO signals in our catchment. If the global temperature continues to rise in the future, we expect that the risk of both droughts and

floods in the study region will also increase.

Keywords: historical archives; catchments; floods; droughts; the southern Chinese Loess Plateau; PDO; solar activities; ENSO

1. Introduction

Usually occurring at catchment scales, droughts and floods are longstanding and devastating climatic threats to mankind (Jiang et al., 2006; Lewis et al., 2011; Scholze et al., 2006; Zhao and Running, 2010; Chen F.H. et al., 2015; Chen J.H. et al., 2015; Ge et al., 2017; Blöschl et al., 2018). They are challenging to predict, mainly due to the extreme variations of precipitation in spatiotemporal scales with the catchment (Darand and Sohrabi, 2018; Liu and Wang, 2011; Min et al., 2011; Chen F.H. et al., 2015; Chen J.H. et al., 2015). Within the context of global warming, the risk of floods and droughts has increased rapidly in different regions (Allamano et al., 2009; Dai, 2011; Pall et al., 2011; Schiermeier, 2011; Blöschl et al., 2018). Therefore, understanding the mechanisms of the regional occurrence of floods and droughts is of enormous importance for risk management and climate change's adaptation and mitigation measures (Scholze et al., 2006).

The biannual shift of the East Asian monsoon front makes the Chinese Loess Plateau (hereafter, CLP) wet in the summer and dry in the winter (An et al., 1991; Liu and Wang, 2011; Wu et al., 2012). The southern CLP, located to the north of River Wei (see Fig. 1), is a famous breadbasket of northwest China since ancient times. The region is also strongly influenced by the East Asian Summer Monsoon (Wu et al., 2012). Floods and droughts are two devastating climatic disasters, which could lead to adverse impacts on the agriculture in the southern CLP. Located to the north of Xi'an City, River Jing, a second-order tributary of the Yellow River, which originates in Jingyuan County (hereafter, JY, see Fig. 1) on the southwest of the CLP, is the main sand source of the Yellow River as it meanders through the semi-arid CLP and discharges into River Wei (the largest tributary of the Yellow River). Within the transitional zone between the CLP and Guanzhong Plain, many tributaries erode the CLP and discharge into River Jing, bringing massive mud and sand, especially during the flood. The common aftermath of floods in the CLP region is devastating human plagues (Ge et al., 2017) and social economic disasters (Chen J.H. et al., 2015). On the other hand, during the drought crops fail in the region, and more adversarially, the clean drinking water for people and livestock becomes limited. Therefore, there is a critical need to appreciate the pattern of reoccurrence and understand the mechanisms of these two natural disasters in order to take predictive and effective adaptation measures against the devastation.

Instrumentational records are too short to conduct a meaningful diagnostic study.

Therefore, historic information from other types of archives may help us to fully understand key characteristics and establish potential mechanisms of the past floods and droughts in the region (Zhao et al., 2019). Chinese historical archives contain high-resolution temporal records of environmental changes and could provide valuable perspectives on paleoclimatic and climatic research (Ge et al., 2003; Jiang et al., 1997; Tan et al., 2008; Wang and Zhang, 1988; Zhang and Crowley, 1989, Chen F.H. et al., 2015; Chen J.H. et al., 2015; Ge et al., 2017). It is therefore crucial to use historic records of droughts and floods to reconstruct the paleo-precipitation features in certain regions. In the year of 1994, Mr Lin Yuan, a professor from Northwest Normal University (China), has compiled an advanced and comprehensive dataset of natural disasters, which includes floods, droughts, earthquakes, dust storms, landslides, plagues, *etc*, in five provinces in northwest China (i.e., Shaanxi Province, Gansu Province, Ningxia Province, Qinghai Province and Xinjiang Province). He has employed over 685 reliable historical archives and published the book of "History of Disasters in Northwest China" (Yuan, 1994, in Chinese), which have listed every disaster for its occurring time in year and exact location. This dataset provides valuable references for analysing disasters in northwest China, which has been used extensively in previous studies (Jiang et al., 1997; Tan et al., 2008; Wang and Zhang, 1988; Zhao et al., 2019).

Previously people have mainly employed an approach of five-level classification (Jiang et al., 1997; Tan et al., 2008; Wang and Zhang, 1988) to reconstruct the climatic variation using historical archives. Based on annual records of both drought and flood events in historical archives, the precipitation level has been classified into five categories: 1) extreme high, 2) high, 3) normal, 4) low, and 5) extreme low. The five-level classification approach is an efficient way for reconstructing the regional rainfall variation, therefore it was widely used in many high temporal resolution paleoclimate studies (Jiang et al., 1997; Stige et al., 2007; Tan et al., 2008; Wang and Zhang, 1988; Zhao et al., 2019). However, this method cannot be used to study the associated pattern between droughts and floods at the same location individually. This is because if during a specific year, there were both drought and flood at one location, the five-level classification would record it as a “normal” year. Basically, the drought has balanced out the flood for the same year at the same location; while in reality, that location has experienced both flood and drought for that year.

In order to appreciate the associated pattern of reoccurrence and understand the mechanisms of floods and droughts, a new method must be developed to quantify flood and drought timeseries separately from the historical archives. In this paper, we have developed a new approach (see Section 3.1 for more details) to create two distinct timeseries, one for droughts and another for floods at our catchment region (see Fig. 1). Focusing on a period during the Qing Dynasty (1646-1949), we have selected ten counties in the middle reaches of River Jing in the southern CLP (see Fig. 1 for counties' locations) to study the occurrence of floods and droughts at catchment scales. The remaining portion of the paper is organized as follows. Our study sites and the climatology are documented briefly in Section 2. Our methodology and the statistics are presented in Section 3, followed by our main results in Section 4. Section 5 summarizes our discussion and key findings.

2. Our Study Sites and the Climatology

Within the middle reaches of River Jing (see Fig. 1), ten counties, namely, Zhengning County (marked as ZN), Ningxian County (marked as NX), Jingchaung County (marked as JC), Lingtai County (marked as LT), Xifeng County (marked as XF), Qingyang County (marked as QY), Binxian County (marked as BX), Changwu County (marked as CW), Xunyi County (marked as XY), and Heshui County (marked as HS), are selected to perform the historical analyses. These ten counties cover an area of about 6,200 square kilometres (see Fig. 1 for the catchment area and locations of ten counties).

The climate in the study area is typical biannual, alternately controlled by East Asian winter monsoon and East Asian summer monsoon (An et al., 1991; Liu and Wang, 2011; Wu et al., 2012), resulting two distinct contrasting seasons (i.e., the dry season, the monsoonal or wet season). In addition to historic archives, we have used 50-year monthly mean climatology records from 1955 to 2005 at meteorological stations within the XF, HS, ZN, and NX counties (http://data.cma.cn). Our modern climatology analyses show that the monthly rainfall is concentrated during the summer season from June to September (see Fig. 2A), which is associated with some high monthly relative humidity (see Fig. 2B). Therefore, we normally expect more floods during the summer season in the region. On the other hand, during the winter to early spring seasons from

November to March, the monthly rainfall is at minimum levels, and the monthly relative humidity in this region is also very low (see Fig. 2B). Therefore, we normally expect droughts during the winter to early spring season in the region.

However, this does not exclude the occurrence of floods and/or droughts in other seasons. For the following case study, we have defined floods as the 5-day accumulated precipitation is more than 100 mm. For example, using daily rainfall observation at Binxian meteorological station (marked as BX in Fig. 1) from 1955 to 2005, we have found one flood event in 1989, which took place in late spring, and did not occur in the summer season (see Fig. 3B). Furthermore, we have defined droughts as the 60-day accumulated precipitation is less than 2 mm. Interestingly, we have also found one drought event in the summer (from July to August) at Binxian meteorological station for the year of 1968 (see Fig. 3C). The 1968 drought did not occur in the expected winter to early spring seasons.

In summary, the middle reaches of River Jing have a typical climate of wet summer and dry winter and early spring so that we normally expect more floods in the summer season, and more droughts in the winter to early spring seasons.

3. Our Methodology and the Statistics

3.1 Quantification and statistics of the historical archives.

Using historical archives, we are facing the issue of very low temporal resolution (e.g., annual records). If we had employed the widely-used five-level classification method (Jiang et al., 1997; Stige et al., 2007; Tan et al., 2008; Wang and Zhang, 1988; Zhao et al., 2019), which defines the hydroclimatic condition (i.e., rainfall) into five categories: 1) extreme high, 2) high, 3) normal, 4) low, and 5) extreme low, we would miss a lot of flood and drought events when both disasters occurred in the same year. Basically, the flood could be cancelled by the drought in many cases. To avoid this problem, we have developed a new method to help us with the regional drought and flood reconstruction from historical archives. Our approach is mainly based on the individual influence of floods and droughts within the catchment. The catchment records of droughts and floods in the selected sites from historical archives were separately counted, and the catchment-averaged values of floods and droughts were used to indicate the intensity of that disaster for the region. In particular, we have chosen ten counties in the middle reaches of River Jing (see Fig. 1) and used the disaster sequences of Yuan (1994). If a county in Fig. 1 has a record of drought in a specific year, we will assign a value of 1. If there is no record of drought, we will assign a value of 0. Next, we have added the assigned values for all ten counties' drought records for a specific year and divided it by ten to derive the catchment averaged drought index for that year (ranging from 0 to 1). This drought index will be plotted in Figs. 4 & 7. Similarly, if a county in Fig. 1 has a record of flood in a specific year, we will assign a value of -1. If there is no record of flood, we will assign a value of 0. Next, we have added the assigned values for all ten counties' flood records for a specific year and divided it by ten to derive the catchment averaged flood index for that year (ranging from -1 to 0). This flood index will be plotted in Figs. 4 & 7. Our derived indices of floods and droughts for ten counties are constructed in a way to reflect the total environmental influences of floods and droughts at catchment scales. For example, if five countries among the ten have experienced droughts in historic archives for the same year, our method will record 0.5 for droughts in that year. The same is true for floods. Our method is different from the five-level classification approach (Jiang et al., 1997; Tan et al., 2008; Wang and Zhang, 1988; Zhao et al., 2019) in that we can distinguish the flood and drought events that have occurred in the same location for the same year. This will prevent the missed signal situation when the same location has both drought and flood that could have cancelled each other in the same year.

3.2 Recent droughts and floods (1960-2005) from daily stational observations

In order to establish the indices of droughts and floods within the catchment for recent years (e.g., after 1955), we have collected the daily observation of precipitation at nine stations located at nine counties, respectively (i.e., NX, ZN, JC, LT, XF, QY, BX, CW, XY in Fig 1) from 1960 to 2005 (http://data.cma.cn**).** Same as in Section 2 above, we have defined a flood event as 5-day accumulated rainfall more than 100 mm, and a drought event as 60-day accumulated rainfall less than 2 mm. A MATLAB program will record one flood (drought) event and plot it against the deep blue background according to its actual values of 5-day precipitation for floods and 60-day precipitation for droughts in colour shades (see Fig. 3 for BX county case). The MATLAB program is enclosed in the supplementary material attached to this article. Similar to our new method in Section 3.1 above, we have assigned "-1" for a flood, and "+1" for a drought among the nine counties. Using the 9-county averaging values, we have derived the catchment-scale sequences of floods and droughts from 1960 to 2005, which are subsequently added to Fig. 7A. We have plotted the timeseries from 1960 to 2005 slightly different from those derived from historic archives from 1646 to 1949 (see Fig. 7A). This is because historic archives have recorded the "actual" disasters in the past, while the modern-day timeseries are based on our definitions of floods and droughts as explained above.

3.3 The periodical analysis.

The REDFIT 35 computer program (Schulz and Mudelsee, 2002) for the periodical analysis was used to identify the key periodicities of our derived timeseries of floods and droughts for the middle reaches of River Jing (1649-1949).

4. Our Results

4.1 Derived timeseries of floods and droughts in the past (1649-1949)

The sequence of droughts and floods in the middle reaches of River Jing from 1646 to 1949 is shown in Figure 4. During the 304-year period, among the ten counties, there are 241 records of droughts within 101 years, and 231 records of floods within 104 years, respectively (see Fig. 6 for details). There are 148 years with either droughts or floods, and 58 years with both droughts and floods over the 304-year period. Among the ten counties, there are eight with at least one record of both drought and flood conditions occurring in the same year (see Fig. 5 for details). LT county has the largest number (33) of both droughts and floods occurring in the same year (see Fig. 5) over the 304-year period. In order to show the strong spatial variation of floods and droughts in out catchment, we have plotted the total records of floods and droughts for ten counties, regardless their occurrence years (see Fig. 6). Within the small catchment of about 6,200 square kilometres (see Fig. 1), the floods and droughts have varied substantially over the 304-year period. For example, LT county had the largest numbers of both floods and droughts (see Fig. 6). The JC and QY counties had very similar numbers of droughts as compared to LT. However, the NX and QY counties had the second largest numbers of floods as compared to LT. Overall, the XY and XF counties had the smallest numbers of floods and droughts during the period.

On the other hand, the occurrences of droughts and floods are almost synchronous on decadal timescales (see Fig. 4). There are frequent occurrences of droughts and floods in the middle of each century, especially in the middle of the 18^{th} and 19^{th} centuries.

Note that the occurrences of both disasters are less frequent at the beginning or end of the 18th, 19th and 20th centuries, but the whole catchment is subject to severe disasters. For example, nine counties experienced floods in 1801, and six counties had droughts and five counties had floods in 1892. In the semi-arid CLP, the climate condition is mainly influenced by two monsoonal systems: 1) The East Asian summer monsoon, which brings in warm and moisture air from the tropical oceans in summer; and 2) The Asian winter monsoon that contributes to cold and dry climate in winter to early spring seasons. Overall, the occurrences of droughts and floods are more frequent during the dry and wet seasons, respectively. Consequently, eight counties from the ten have records of both drought and flood conditions occurring in the same year (see Fig. 5).

4.2 A comparison of our floods and droughts vs decadal solar activities and global/regional temperatures

We have compared our droughts and floods in the middle reaches of River Jing with the reconstructed solar irradiance (Lean et al., 1995; Lean and Rind, 1998; Solanki and Fligge, 1999) and atmospheric temperatures (Ge et al., 2003; Mann and Jones, 2003) (see Fig. 7A,7B,7C). As marked by the light orange bands in Figure 7, three epochs of higher frequency of both droughts and floods in Fig. 7A are lined up with the higher values of solar irradiance (red and wine lines in Fig. 7B), the reconstructed global temperature (purple line in Fig. 7C), and the winter temperature derived from historical archives (violet line in Fig. 7C). The occurrences of droughts and floods are frequent in our study region during relatively warm periods that correspond to more solar activities and warmer atmospheric conditions. On the contrary, the frequency of droughts and floods is lower during relatively cool periods that correspond to less solar activities and cooler atmospheric conditions. In particular, the Maunder Minimum (1645-1715, see the light blue band in Fig. 7) (Eddy, 1976; Owens et al., 2017; Vaquero et al., 2002), corresponding to the middle and coldest episode of the Little Ice Age (Mann et al., 2008), is well known as a period of very low solar activity (Hoyt and Schatten, 1998; Lean et al., 1995), and our historical archives also record less occurrences of droughts and floods in the middle reaches of River Jing. During the Maunder Minimum among ten counties, there were only thirteen droughts and four floods within the 70-year period. The second cooler condition is associated with the Dalton Minimum (1790-1820, see the light blue band in Fig. 7). During the Dalton minimum, the number of sunspots at the peak of the solar cycles was about one-third of that observed during normal solar cycles. The three solar cycles that occurred during the Dalton Minimum also had unusually long periods of sunspot inactivity (Hoyt and Schatten, 1998; Lean et al., 1995). During the 30-year period, our historical archives only recorded fifteen droughts and eleven floods among the ten counties. On the other hand, the occurrences of droughts and floods were much higher during the warm periods. For example, from 1740 to 1780, there were fifty-one droughts and sixty floods within the 40-year period; from 1820 to 1865, there were sixty-seven droughts and ninety floods within the 45-year period; and from 1960 to 2000, there were one hundred and fourteen droughts and one hundred and twenty floods within the 40-year period. On the average, the frequency of droughts and floods during the warm periods is 13.8 times higher than that in the Maunder Minimum (4.0 events per year in the warm periods, but only 0.29 event per year during the Maunder Minimum). The strong link between reconstructed mean temperatures and two natural disasters (droughts and floods) suggests that global and regional mean temperatures (climatic conditions) could have played some important roles in the occurrences of droughts and floods in the study region. This strong link is confirmed partially by a European study of Blöschl et al. (2018).

4.3 A comparison of our floods and droughts vs PDO and ENSO indices

The results of spectral analyses on the flood and drought time series (see Fig. 8) show that both sequences have a periodicity of ~11-year corresponding to the Schwabe sunspot cycle, which provides strong evidences about the potential control of solar activities on the occurrences of floods and droughts in our study region. The spectral analyses also show a periodicity of ~2-5-year for both sequences. This typical periodicity could be linked directly to ENSO (Graham and White, 1988; Li et al., 2013), suggesting that the equatorial Pacific Ocean sea surface temperature (hereafter, SST) may also have some influence on regional precipitation patterns in our study region. The impacts of ENSO on the monsoonal climate inside China has been well studied previously (Liu et al., 2016; Liu et al., 2018; Ouyang et al., 2014; Su and Wang, 2007; Wu et al., 2012), mainly due to the dominated control of ENSO on interannual climate variability globally and over East Asia. Our spectral analysis has confirmed this. In addition, as shown in Figs. 7A & 7D, during the relatively warmer episodes of ENSO, the middle reaches of River Jing had more frequent floods and droughts. Due to the uncertainty in reconstructed Nino3.4 index and our derived sequences of floods and droughts from historic archives, it is challenging to directly correlate Nino3.4 index with our timeseries.

The PDO index (Trenberth and Hurrell, 1994; Zhang et al., 1997) is based on the thermal conditions of North Pacific Ocean (north of 20^{o}N). It is normally constructed as the principal component of the leading EOF of monthly SST anomaly over the North Pacific Ocean. The PDO is detected as the leading mode of multi-decadal variability in SST in extratropical northern Pacific (MacDonald and Case, 2005). Warm (Cool) surface water over the northern part of Pacific Ocean corresponds to positive (negative) phases of PDO. Similar to ENSO, PDO has dominated the decadal scale climate variability globally and in East Asia (Ouyang et al., 2014; Shen et al., 2006). As shown in Figs. 7A & 7E, during the relatively warmer episodes of PDO, the middle reaches of River Jing had more frequent floods and droughts. Again, due to the uncertainty in reconstructed PDO index (MacDonald and Case, 2005) and our derived sequences of floods and droughts from historic archives, it is challenging to directly correlate PDO index with our timeseries.

5. Discussions and Summary

The anomaly of the spatial pattern of global precipitation depicts the occurrences of droughts and floods in different regions. The precipitation pattern in southern CLP is mainly controlled by the moisture availability transported in East Asian summer monsoon from the low-latitude ocean (An et al., 1991; Liu and Wang, 2011; Wu et al., 2012). The interannual and decadal SST oscillations in the Pacific Ocean, dominated by ENSO and PDO (Graham and White, 1988; MacDonald and Case, 2005; Ouyang et al., 2014; Shen et al., 2006), have great influences on the spatial pattern of global precipitation (McCabe et al., 2004; Mochizuki et al., 2010; Ouyang et al., 2014, Wu et al., 2012), causing droughts and floods in many places globally. Within the context of global warming, ENSO variability appears to be intensified (Fedorov and Philander, 2000; Li et al., 2013; Timmermann et al., 1999; Zhang et al., 2008), and the precipitation extremes in many places tend to be more frequent, consequently (Blöschl et al., 2018). This will contribute to intensified floods and droughts in different seasons for our catchment of River Jing.

In summary, our main results provide definite and strong evidences that the occurrences of droughts and floods in the middle reaches of River Jing are synchronous with solar activities and global/regional mean temperature reconstructions, at least on decadal timescales. The frequency of these disasters (droughts and floods) responds closely to elevated global and regional mean temperatures. Our main hypothesis is that the atmospheric temperature rises responding to high levels of solar activities (Lean and Rind, 1998; Nesmeribes et al., 1993), which in turn result in intensified atmospheric general circulation patterns, causing anomalous spatial distributions of precipitation in the region. This will directly contribute to the higher occurrence of droughts and floods in our study region. Our analysis also shows that from 1646 to 1949, droughts and floods have the natural decadal variability, which is mainly controlled by the solar activities (Lean et al., 1995; Lean and Rind, 1998; Solanki and Fligge, 1999; Solanki et al., 2004). In the context of higher solar activities (Solanki et al., 2004) and the general global warming (Fischer et al., 2018; Rogelj et al., 2011; Blöschl et al., 2018), the risk of both droughts and floods in our study region may increase.

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